Background & Introduction to **Mission Data System & Other Software Architectures**

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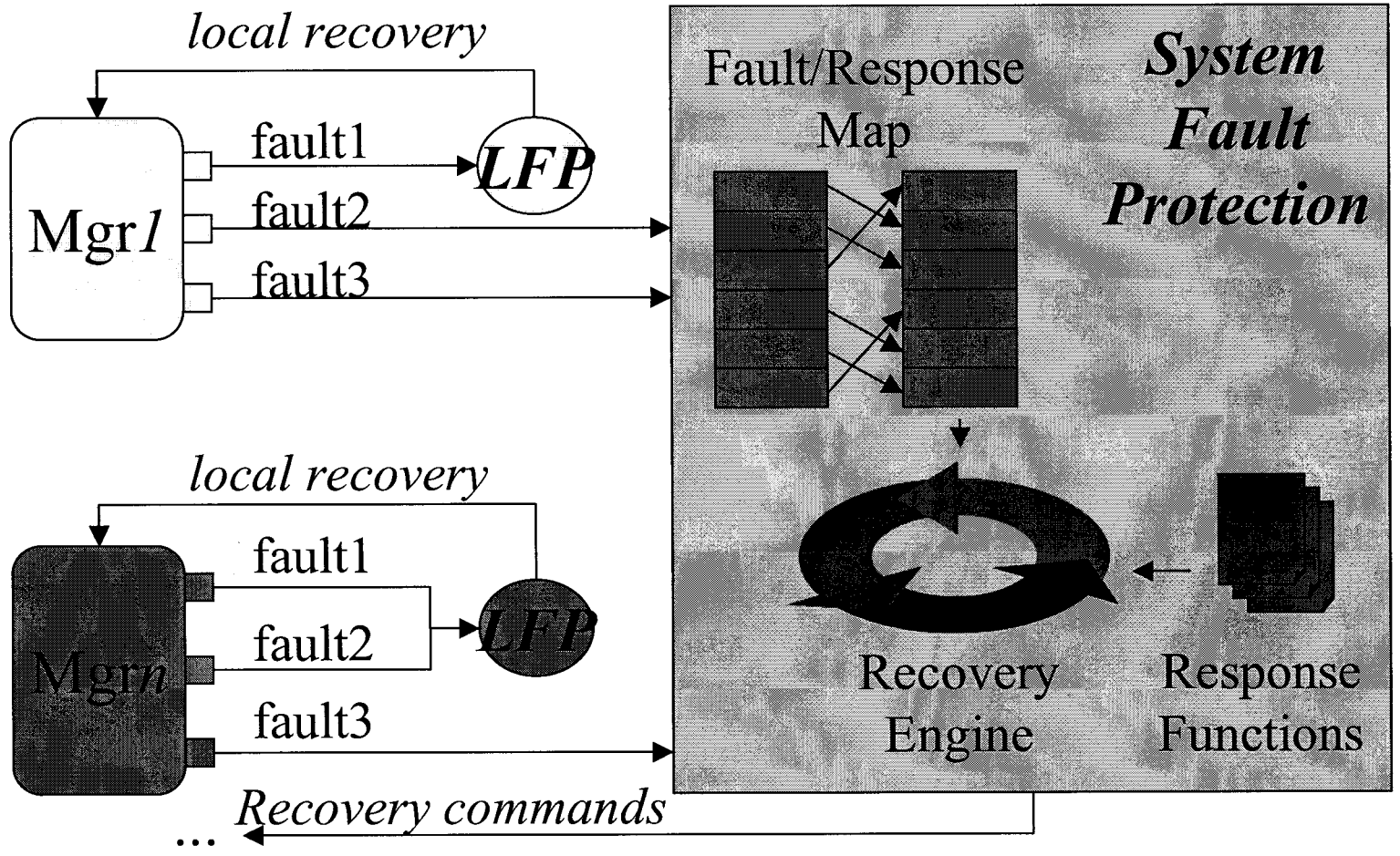
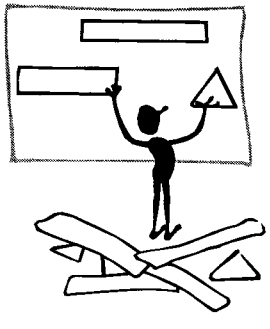
Background

Then:		*Now:*
• Big-budget missions spaced <u>years</u> apart	→	• Better-faster-cheaper missions, <u>monthly</u> launches
• Deep space missions tend to be one-of-a-kind	→	• Still true, but they share common needs: pwr, comm, acs, nav, fault protection, ...
• Limited processor speed & memory, highly tuned flight software	→	• Processor speed & memory no longer so limiting
• Little flight software reuse	→	• Need to apply s/w engineering resources more effectively • Thus, MDS project initiated in April 1998 to rethink mission software lifecycle

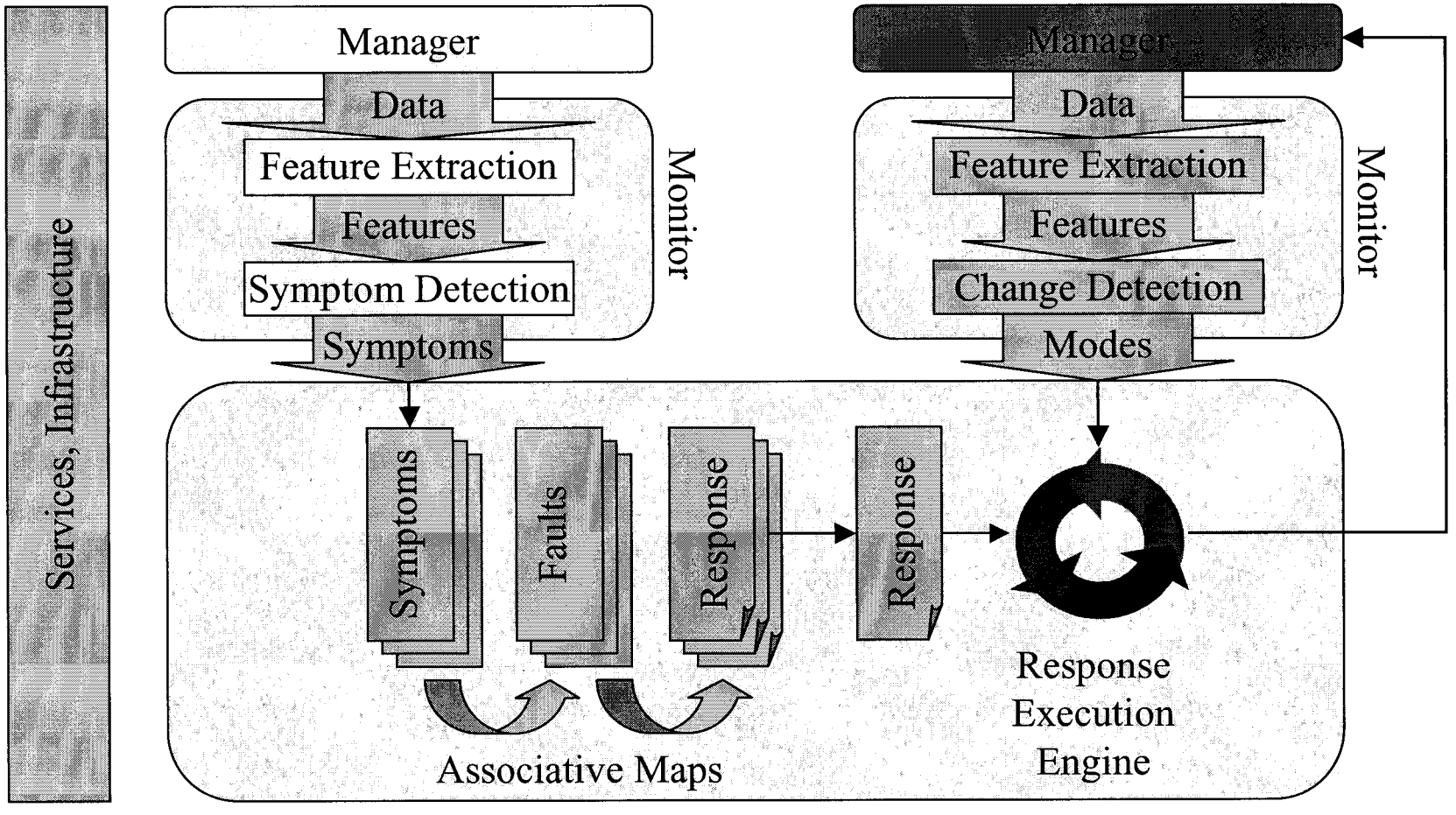
MPF's Fault Protection ⇒ a hand-crafted jewel

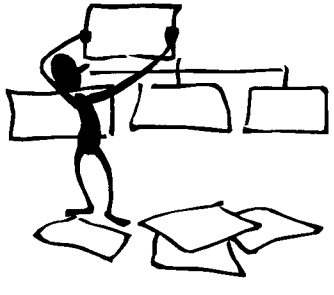




- ⇨ Response functions are hand-written C functions
- ⇨ Monitor designs vary per manager

DS1's Fault Protection ⇒ the little engine that could...

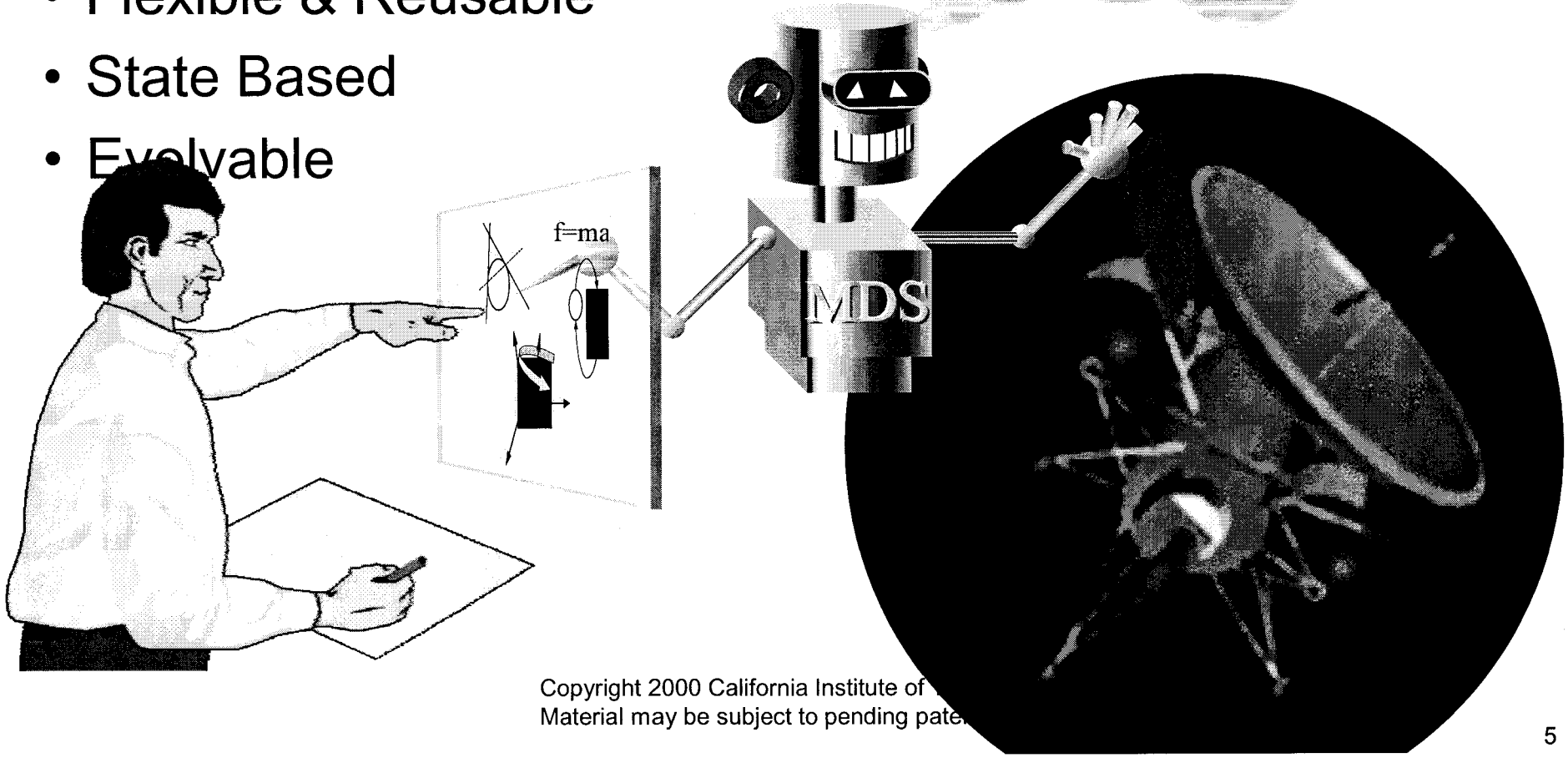




- ⇨ Response functions are generated from statecharts
- ⇨ Monitor designs follow a uniform architecture

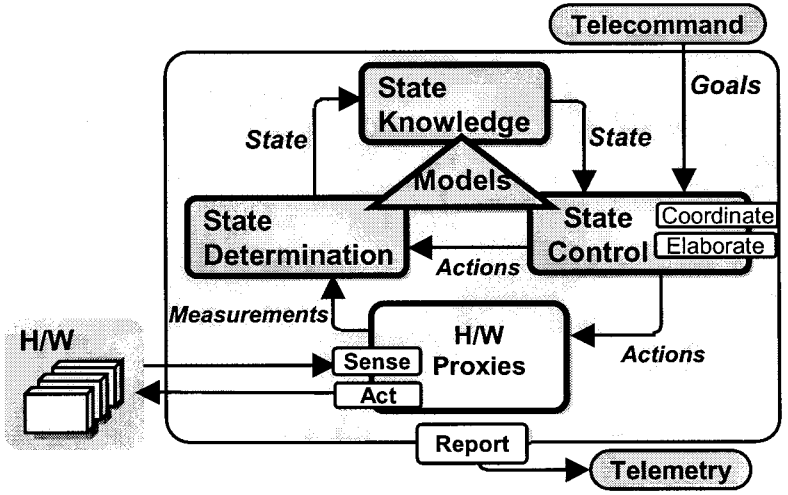
MDS Spans the Mission and System

- A Unified Flight, Ground, and Test Ar
- An End-to-End Information System
- A Multi-Mission Enterprise
- Flexible & Reusable
- State Based
- Evolvable



Mission Data System

Unified Flight, Ground &Test Data System Architecture for Space Missions



Objectives

- More effective use of software engineering resources
- Earlier collaboration of mission, system & software design
- Unified flight, ground & test architecture
- reusable components & simpler interfaces
- Goal-directed operations
- Automation
- Evolvable to in situ exploration & other autonomous applications
- Customer-controlled complexity:
  - Simple to sophisticated, depending on mission requirements
  - Make it easy to exercise options

Key Architectural Themes

- Plan to migrate capability from ground to flight
- Formal representation and manipulation of state is central
- Express domain knowledge in models, not program logic
- Goal-directed operation specifies intent; simplifies operations
- Closed-loop control for real-time in situ reaction to events
- Fault protection is integral part of design, not an add-on
- Real-time resource management (for power, fuel, etc)
- Clean separation of state determination from control
- State uncertainty is acknowledged & used in decision-making
- Clean separation of data management from data transport
- Navigation and attitude control build from common base
- Upward compatibility through careful design of interfaces

Customers

- X2000 First and Second Deliveries
- OP/SP missions:
  - Europa Orbiter
  - Pluto Flyby
  - Solar Probe
- Space Interferometry Mission (SIM) — *under study*
- Potential application to Mars and other programs
- DSMS (Deep Space Mission System)

The 3 Meanings of "MDS"

- **MDS, the *architecture:***
  - establishes a unified approach to flight, ground, and test systems for space missions
  - reflects a dozen architectural themes aimed at: simplified operations, adaptability, clean design, evolvable autonomy
- **MDS, the *project:***
  - is managed by TMOD (Telecommunications & Mission Operations Directorate) at JPL
  - is a "change agent" at JPL defining processes and aligning resources, technology, and organizations
  - is working with first mission customer *Europa Orbiter* toward a November 2003 launch
- **MDS, the *system:***
  - is a set of frameworks and examples to be *adapted* to meet the needs of each mission

8 MDS Themes

The Meaning of "Theme"

These are "themes" in the sense that they:

- have broad impact on operations or software structure
- are notably different than current practices

These themes are not novel ideas; they:

- are sensible design concepts drawn from control systems, robotics, software engineering, computer networking, artificial intelligence, etc

Theme 1: An Architectural Approach

Traditional Approach:

- Subdivide along conventional lines
  - *Flight - Ground - Test*
  - *Design - Test - Operations*
  - *Engineering - Science*
  - *ACS - Nav - Power - Prop - Telecom - Thermal …*
  - *Downlink - Uplink*
- Apply customized solutions within each realm
- Integrate and iterate, integrate and iterate, …
- Minimal re-use

MDS Approach:

- Construct subsystems from architectural elements, not the other way around!
  - Find the common problems and create common solutions
  - Tailor the general solutions to the particular problems
- Managing interactions is the foundation of a design
  - Find interaction mechanisms
  - Create coordination services
  - Use these common services rather than private function-to-function agreements

Theme 2: Ground-to-Flight Migration

MDS takes a unified view of flight and ground capabilities because of opportunity and need:

Opportunity

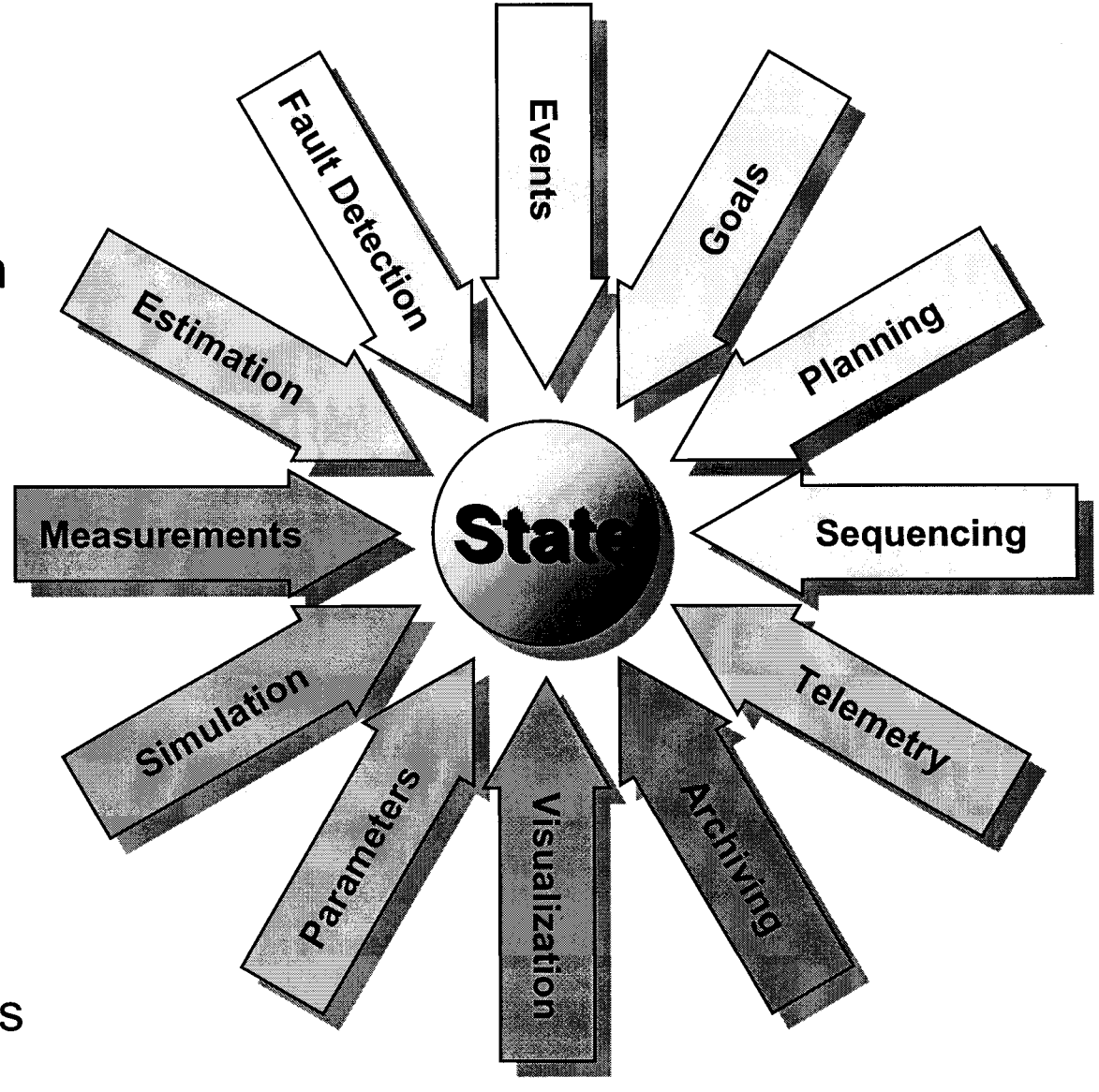
- more powerful flight computers can perform more functions
- capabilities situated on ground can be migrated to flight when operational characteristics well understood and routine
- migration reduces operational burden and may reduce demands on DSN (deep space network)

Need

- round-trip light-time delay will preclude earth-in-the-loop control for some missions:
  - Pluto fly-by will occur with a round-trip delay of 9 hours
  - autonomous landing on comet while avoiding gas jets

Theme 3: *State* is a Unifying Idea

- System state is formally analyzed to discover its constituent components
- Each is represented with a model, including effects from other states
- Measurements (with models) determine state
- Goals (with models) control state
- Communication, visualization, simulation, and many other functions also use state



Theme 4: Express Knowledge in Models

Example Model Types

- Relationships on state
  - *Power varies with solar incidence angle*
- Conditions on state
  - *Gyros saturate above a certain rate*
- Sequential state machines
  - *Some sequences of valve operations are okay; others are not*
- Dynamical state models
  - *Accelerating to a turn rate takes time*

Uses for Models

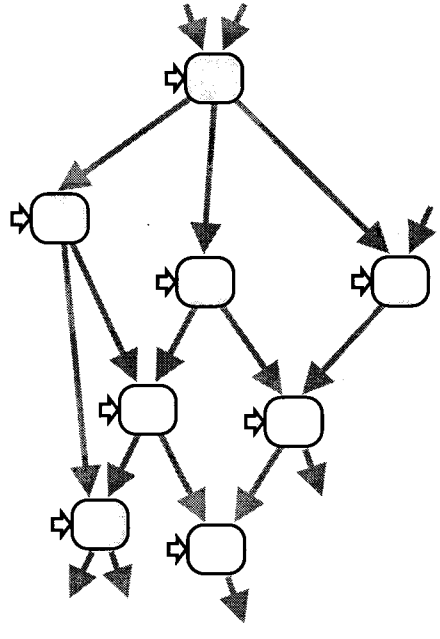
- Process a measurement
  - *Tracker updates indicate that estimated turn rate is too high*
- Prepare for the future
  - *Sun occultation will occur soon*
- Decide what actions to take
  - *The thrusters cannot be used until they are heated*
- … or Not to take
  - *Turning that instrument on now will use too much power*
- Discover faults
  - *It wasn't supposed to do that*

Theme 5: Goal-Directed Operation

- A goal specifies *intent*, in the form of *desired state*.

Definition

- A *goal* is a constraint on the value of a state variable during a time interval.
- Goal-directed operation is simpler because a goal is easier to specify than the actions to accomplish it.
- Goal-achieving modules (GAMs) attempt to accomplish submitted goals.
- A GAM may issue primitive commands and/or sub-goals to other GAMs.
- A GAM must either accomplish a goal or responsibly report that it cannot.

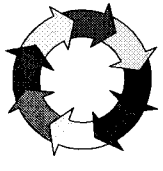


Theme 6: Closed-Loop Control

Problems:

- Open-loop control is both brittle and risky because it is "flying blind".
- Open-loop control forces ground operators to consider many failure scenarios when planning a sequence.
- Open-loop control precludes missions that demand quick reaction to unpredictable events.

Solution:



- Determine spacecraft state in real time from onboard measurements, not on time-delayed ground predictions.
- Employ closed-loop controls onboard to accomplish goals using continuously updated state feedback..

Theme 7: Integral Fault Protection

Anecdote:

- The day that they enabled fault protection in Cassini AACS they learned more about the spacecraft in one month than they had in the previous 6 months. *[Ras]*

Definition:

- Fault protection = fault detection, localization, reconfiguration, and recovery.

Approach:

- In MDS, fault protection will be an integral part of the design—not an add-on—because it is:
  - essential for robust control
  - extremely valuable for verification and debugging

Theme 11: Separate Data Management from Data Transport

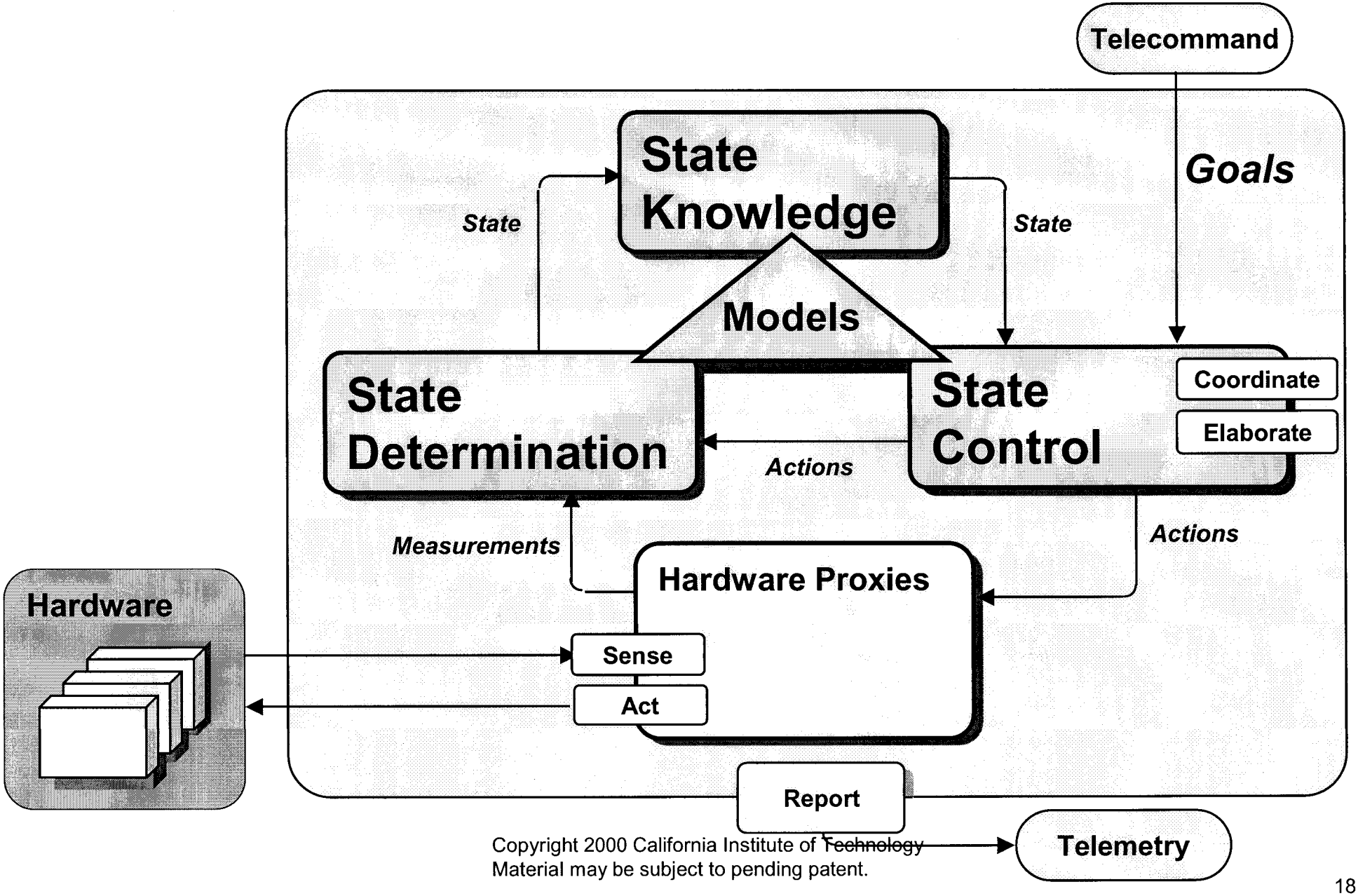
Problem:

- Traditionally flight and ground data management has been tightly coupled with data transport making the design, programming, testing, and evolution harder for both.

Solution:

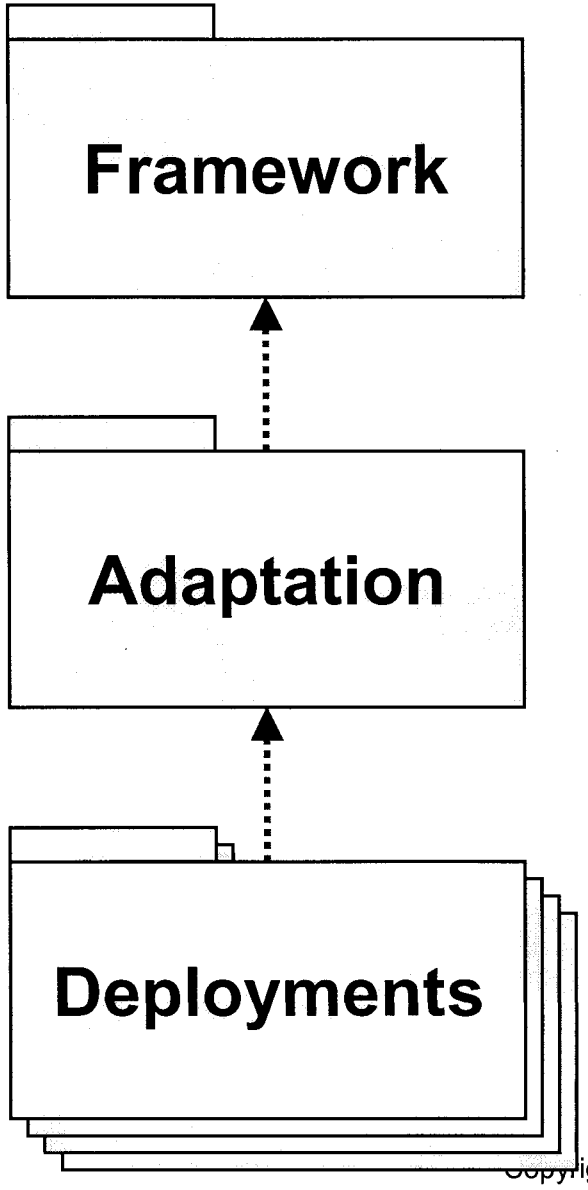
- Keep data management and transport cleanly separated
  e.g. CCSDS packet format known only to data transport
- Elevate data products as entities in their own right:
  - exist as objects and files
  - can be used onboard
  - can be updated, summarized, aged, etc.
  - not necessarily destined for ground
- Data transport can access *any* data products, as needed
- Decoupling allows independent improvements

Top Level View of Architecture



The Common Model

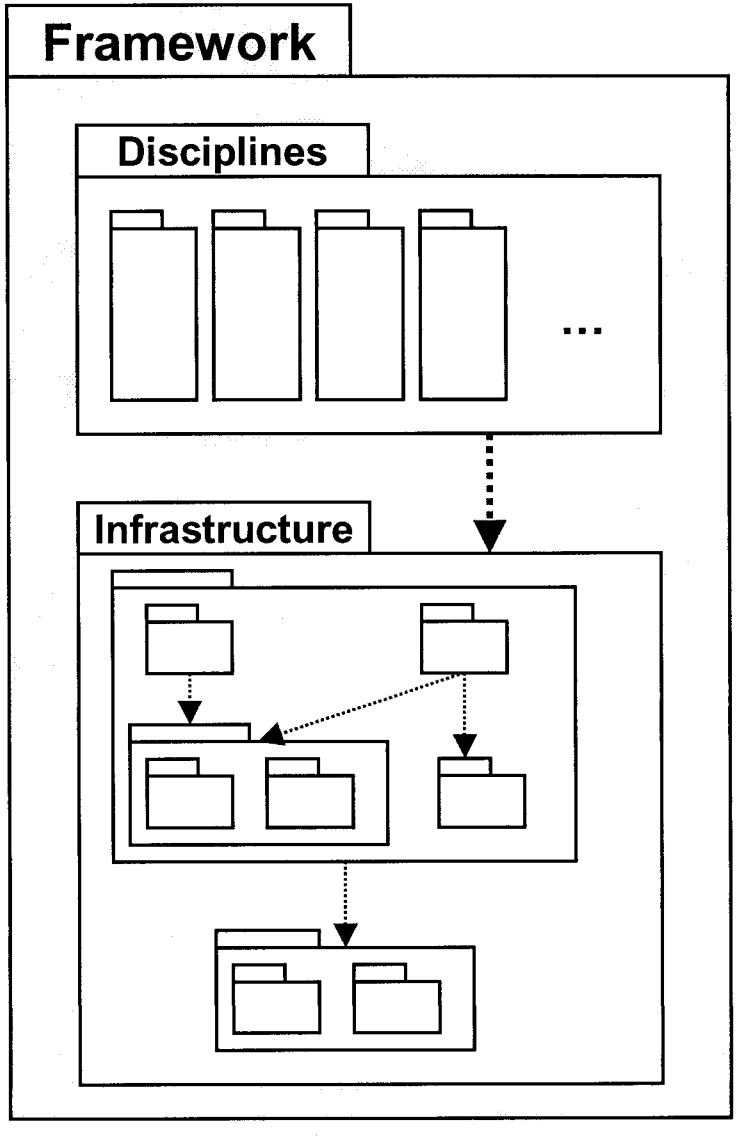
Common Model Structure and Use



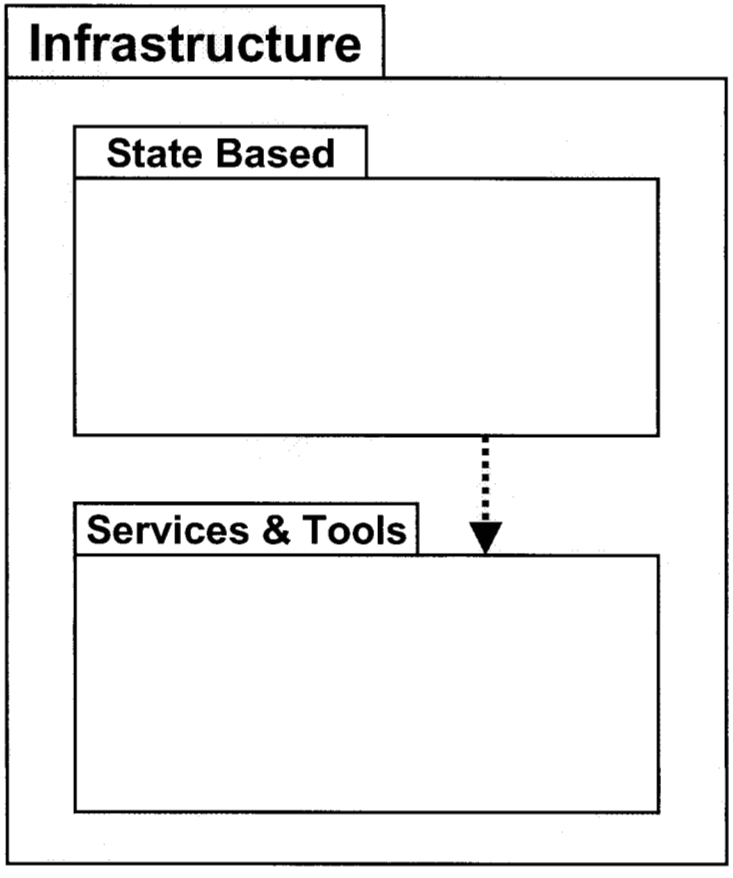
- **Framework** is the collection of most core classes within the MDS architecture
  - Developed and maintained exclusively by MDS
  - Uniform (except for versioning) across MDS adaptations
- Each project does an **Adaptation** of the framework
  - Captures project requirements and scenarios
  - Extends framework classes to address functions and configurations specific to the project
  - Reusable extensions are generalized (if necessary) and moved to the framework
- Several **Deployments** of the adaptation are defined
  - These are the executable configurations to be used in various settings (test beds, flight

- Disciplines extend and customize the core infrastructure*
  - Partitioned as peers for modularity, acknowledgement of discipline vagaries, and the ability to aggregate functionality across disciplines as necessary

* Infrastructure
  - All of the classes embodying core, generic features, concepts, and services
  - Internally layered (hierarchical) to maximize reuse and uniformity, and to build more complex structure in manageable steps



Infrastructure



- Infrastructure is divided (more or less) into …
  - The State Based Architecture
    - Elements upon which most of the operational structure of the software is built
  - Services and Tools
    - Core elements that provide fairly conventional computing capabilities

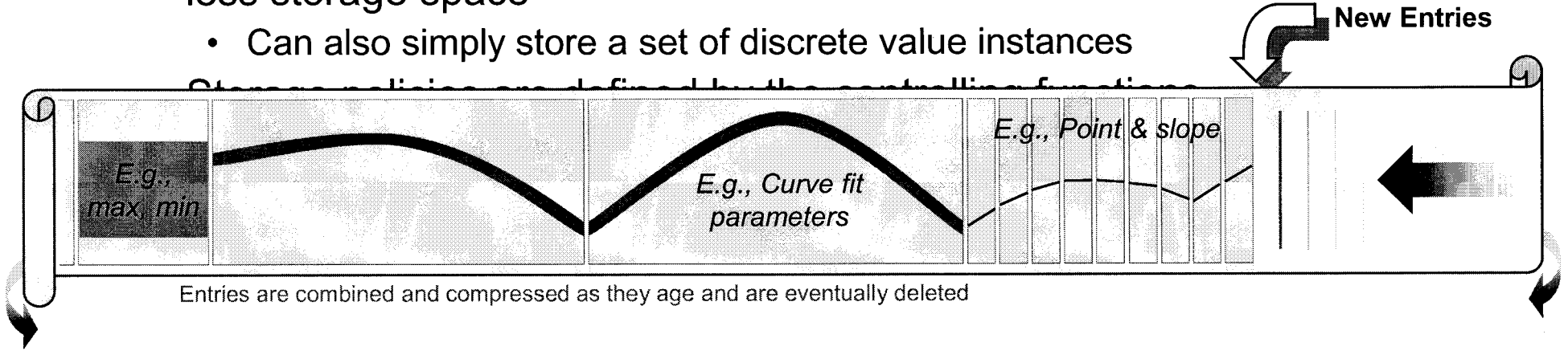
Services
(Data Management & Transport)

Data Management (DM)

- Persistent storage, retrieval and deletion of data objects
  - Built upon physical storage abstraction layer provided by OS
  - Standard serialization methods
  - Buffered access
    - Facilitate frequent access
    - Hold before committing NVRAM write cycles
  - Data base cataloging and queries by name or property
- Data Products
  - Framework for most DM content
    - Science instrument and engineering data
    - Comprised of metadata plus configurable content
    - Each type stored in cataloged collections
      - Collections of collections are possible
  - Both the standard storable unit (in simple collections) and the standard transportable unit (in transport-proxy collections)

More Data Management

- Value histories
  - A container mechanism supporting functions that produce values over time
  - Encapsulate a "back-end" interface to data management persistent storage and data transport.
    - Can be stored and transported as data products
  - Leverage the use of models to preserve continuous information using less storage space
    - Can also simply store a set of discrete value instances

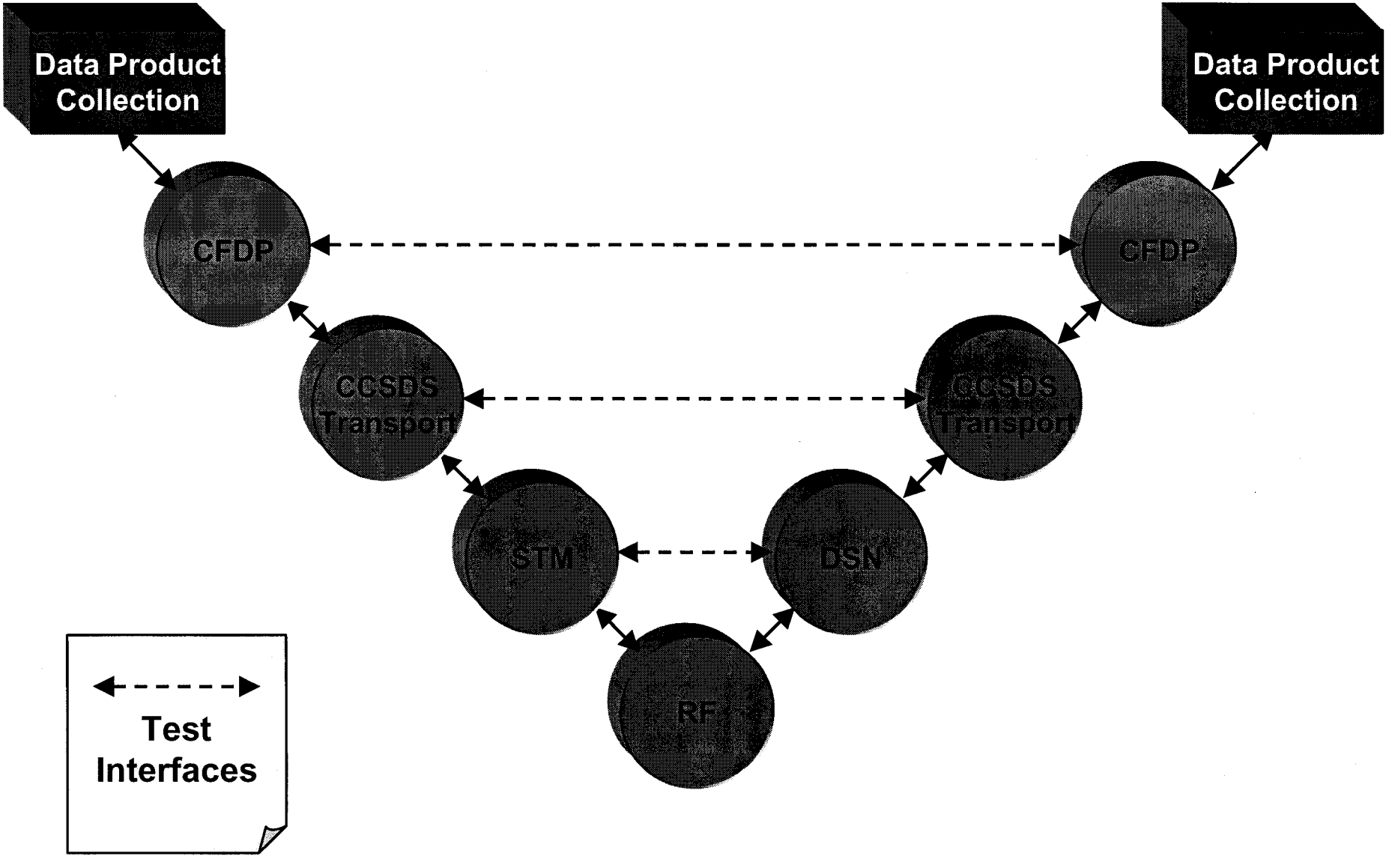


- Name services
  - Global registry for name (character string) to value (integer) conversions
  - Along with standard serialization methods, eliminates a large portion

Data Transport (DT)

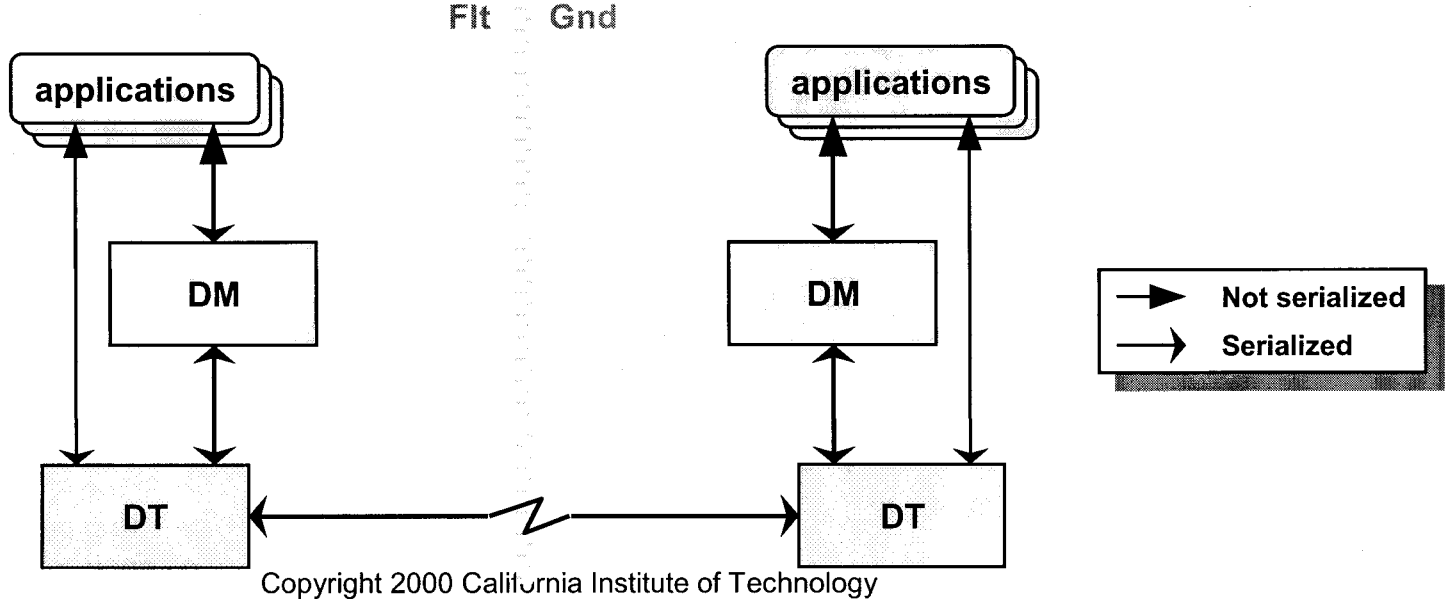
- Encapsulation of space telecom links
  - Bi-directional transport
    - DSN ↔ S/C
    - Proximity space links (formations, orbiter ↔ lander, …)
  - Direct file/object transport
  - CCSDS, reliable transport protocols (e.g., CFDP), …
  - TMOD data delivery services
  - IPC with support for QoS on space links
    - Latency, errors, rate, volume, etc.
- Interface to telecom hardware
  - Management
  - Data streams
  - Radiometric data (Doppler and range) for navigation
- Data link management
  - Data rate selection
  - Relay / forwarding

Data Transport Layers



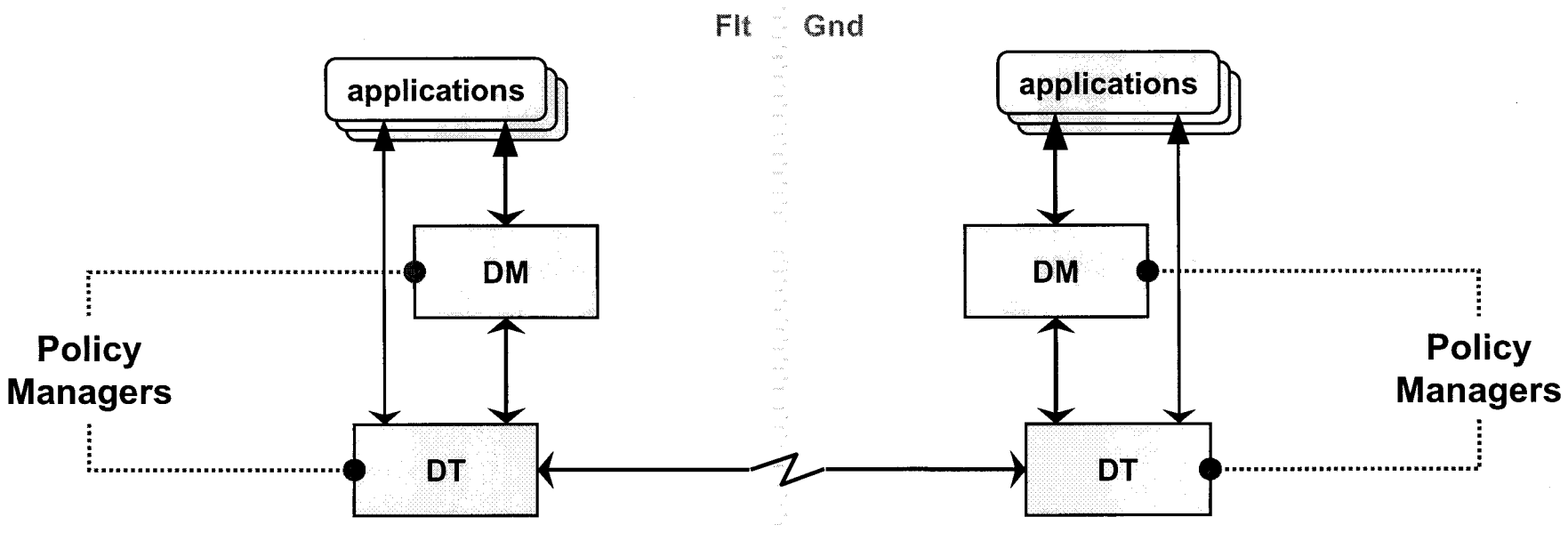
DM/DT Roles

- Both DM and DT are visible but non-intrusive to applications
  - Can access storage and transport (via IPC) independently
  - Storage and transport use each other
- Both DM and DT have a distributed deployment (resident on all nodes)
  - Unified design with corresponding flight and ground elements in each
  - Symmetric across the flight/ground interface
    - Anything you can send down you can also send up



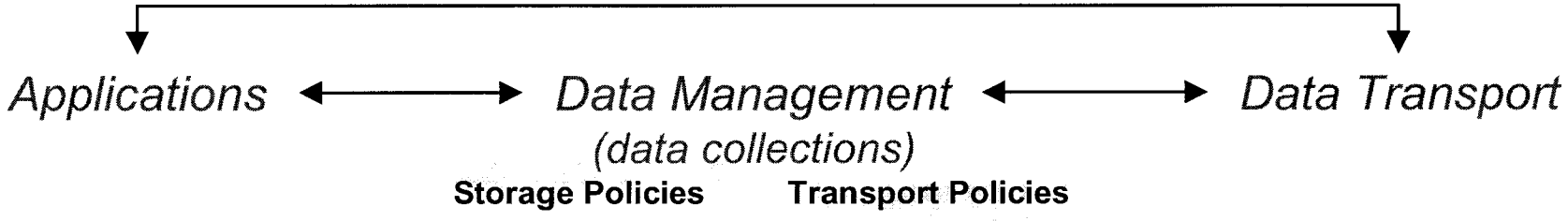
Policies

- DM and DT are controlled mainly via policies
  - Some applications may change the contents of public collections, and…
  - A few applications may interact directly via data transport, but…
  - No applications (except policy managers) directly manipulate storage and transport functions



DM Policies

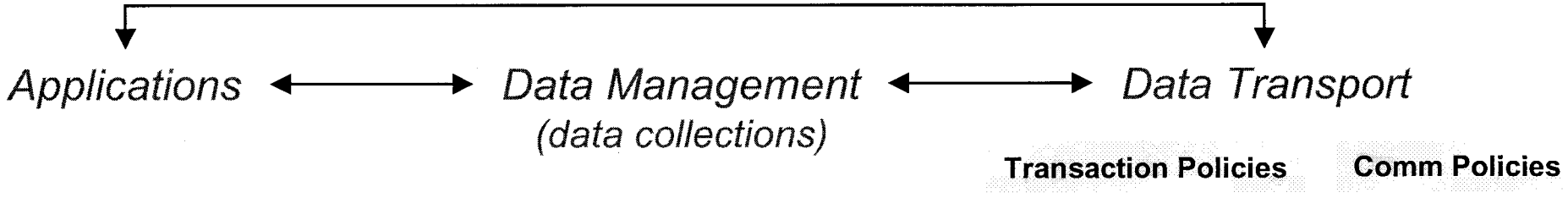
- DM policies establish a desired QoS for each data collection
  - Storage policies establish…
    - Level of persistence
    - Type and degree of compression
  - Transport policies (for transport-proxy collections) establish…
    - Schedule and timeliness
    - Priority
    - Required completeness and continuity



- Status of each data collection
  - Catalog of contents
  - Storage allocation status
  - Transport status per transportable data product

DT Policies

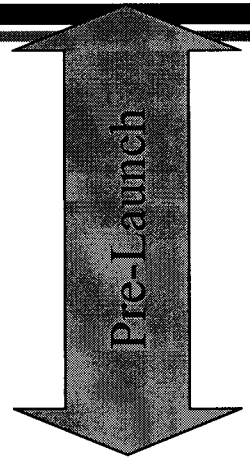
- DT policies establish a desired QoS for each link
  - Transaction policies establish…
    - Acknowledgement requirements
  - Comm policies establish…
    - Adaptation to link characteristics
      - E.g., data rate and volume transportable
    - Latency requirements

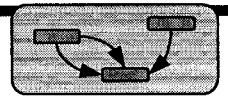


- Status of current link
  - Bit error rate (receiving side)
  - Expected completion time of link
  - CFDP file transfer status
    - Acknowledged versus unacknowledged transactions

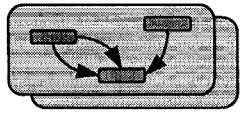
What's next for Nicolas?

System engineers take charge with Statecharts

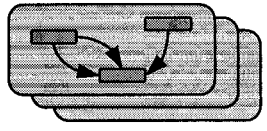




Design prototype

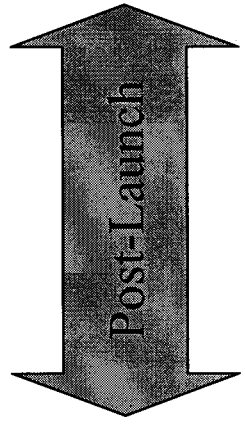


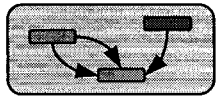
Complete design



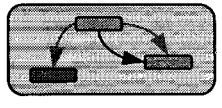
As launched

Long-term maintenance

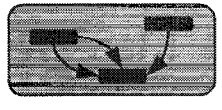




Changing actions performed in a state



Adding/deleting states and transitions



New behavior

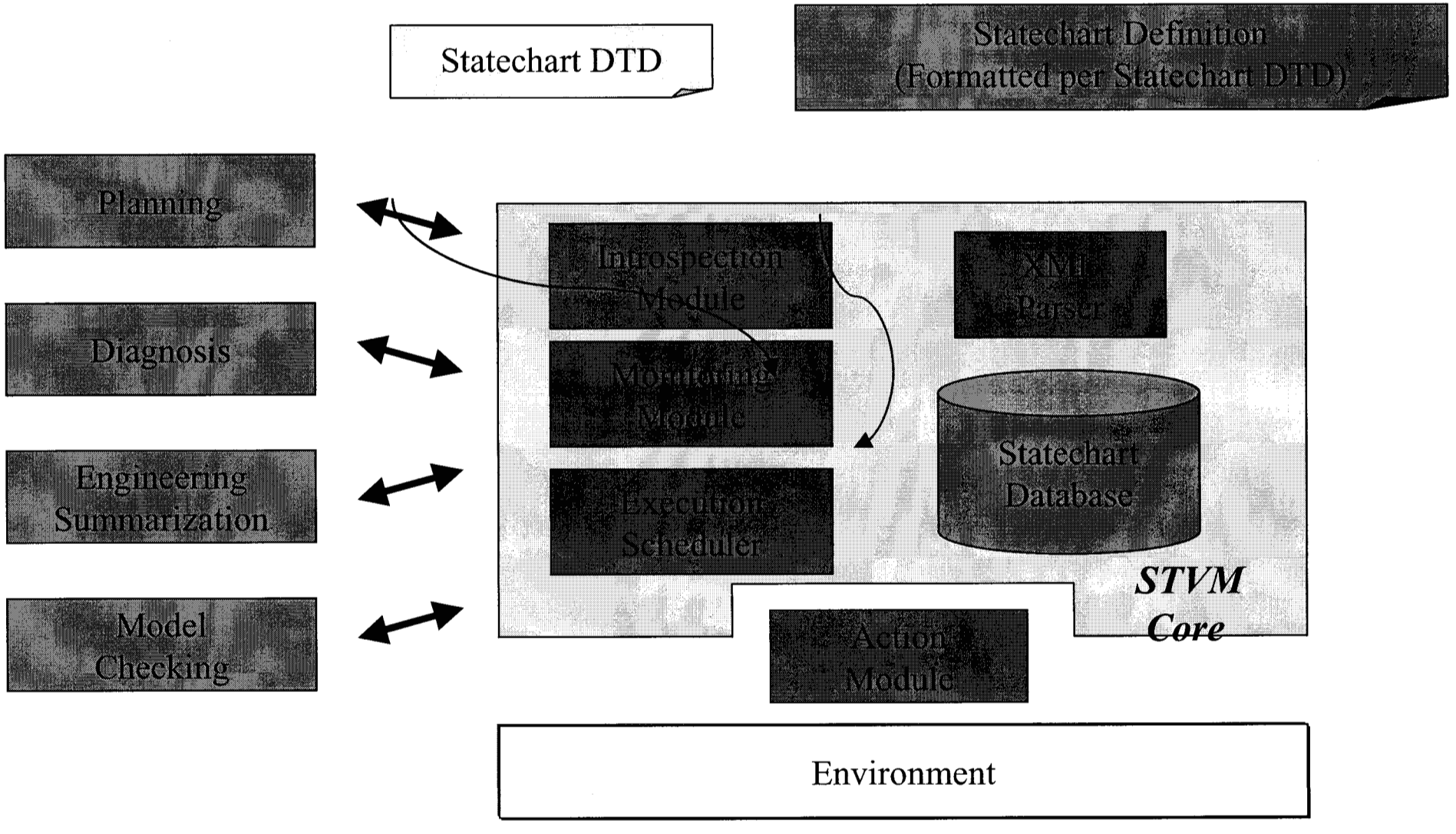
An STVM facilitates long-term maintenance because of:

- low-bandwidth requirements

- life-cycle continuity of system engineering practices

- no software programming required

STVM Architecture



STVM Internal Architecture